NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3050

A PHOTOGRAPHIC METHOD FOR DETERMINING VERTICAL VELOCITIES OF AIRCRAFT IMMEDIATELY PRIOR TO LANDING

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SUMMARY

A photographic method employing a long-focal-length (40-inch) lens for obtaining statistical data on vertical velocities of aircraft immediately prior to landing contact developed for use with land-based airplanes is described. It requires no instrument installation on the aircraft or interference with airport operation and employs relatively simple data reduction. Vertical velocities can be obtained by this method within a probable maximum error of ±0.31 fps.

INTRODUCTION

One of the airplane components which represents a considerable part of the gross and net payloads of commercial and military aircraft is the landing gear and its related supporting structure. The relative weight of the landing gear continues to be high because of the unavailability of suitable design data. In order to design the lightest landing gear that will still be commensurate with adequate safety of operation, sufficient statistical data on typical aircraft operations must first be obtained.

One of the principal design parameters which will give suitable data for determining landing-gear size is the vertical velocity of the aircraft at impact. Inasmuch as only a limited quantity of these data has been obtained, the National Advisory Committee for Aeronautics has undertaken the measurement of vertical velocities on a large number of aircraft in normal commercial operations. A study of previously developed techniques and instrumentation for obtaining these data was made and it was felt that none were quite suited to the present needs. Information concerning these methods may be found in references 1 to 5. The equipment and method described herein were then developed. Some results obtained with this equipment are presented in reference 6.

Because of the photographic limitations of the equipment, records can only be taken when the horizontal visibility is at least of the order of 1,000 feet and when the light is sufficient to produce readable photographic images. Sinking-speed data, therefore, can only be obtained when the operational conditions are within these limits. Although statistical sinking-speed data including landings obtained under night, bad-weather, or blind-flying landing conditions would be invaluable additional information, obtaining these data is not yet possible with the present method. Inasmuch as the quantity of statistical data of sinking speeds at landing of land-based aircraft under any conditions is limited, it is felt that statistical sinking-speed data obtained under good visibility conditions should still be useful.

INSTRUMENT REQUIREMENTS

In order to carry out the investigation of vertical velocity at landing impact on a large number of aircraft in normal commercial operations, it was felt that an instrument that would meet or closely approach the following requirements should be used:

(1) No modification to or installation on the aircraft should be necessary.

(2) The instrument should be suitable for obtaining statistical data economically.

(3) The vertical velocities obtained should be the vertical velocities at landing contact.

(4) The vertical velocities obtained should have a maximum probable error of approximately ±0.25 fps.

(5) The instrument should be adaptable for commercial or military operation.

(6) The instrument should not interfere with airport operation and should preferably be capable of operation away from active runways. It should also cover as much runway as possible in order to obtain the maximum number of landings.

(7) The instrument should be rugged, portable, and easy to operate and maintain over extended periods.

(8) The data reduction should be simple.

After due consideration, a photographic method was chosen.

DESCRIPTION OF APPARATUS

Although the various methods already in existence were suited for their particular purposes, it was felt that they did not fulfill the requirements of the present problem as closely as desired. Therefore, the photographic method described herein was developed to meet the specific requirements previously listed. This method utilizes a long-focal-length-lens camera installed at a relatively long distance from the runway (750 to 950 feet). The camera tracks the landing airplane in azimuth only over a total range of 60° about its normal setting to the runway. This range amounts to about 900 feet of runway length for usual operating distances from the runway.

Three views of the apparatus are shown in figures 1, 2, and 3. A 35-millimeter Mitchell camera, driven at 25 frames per second by a 400-cps synchronous, three-phase, 120-volt motor, is attached to a barrel-mounted, 40-inch (101-centimeter) f/5.6 telephoto lens. The complete camera unit rests on three adjusting screws which sit on pads fixed to a rigid plate which in turn is mounted on a shaft set in preloaded thrust ball bearings. The camera is equipped with accurate cross levels which are used not only to level the camera but also to right the shaft axis to a position normal to the earth's horizontal. The righting of the shaft axis is accomplished by four jacks used at the corners of an 8-foot by 10-foot trailer. Because the shaft housing and camera unit are rigidly mounted to the trailer, raising or lowering the corner jacks effectively controls the shaft-axis position. Use of a trailer as a base mount facilitates transportation to different locations, as well as operational flexibility at any given airport site. For tracking the landing aircraft a reticle type of gunsight is used and is mounted on a T-bar above the lens barrel.

Azimuthal position of landing aircraft is recorded by means of cam-operated microswitches which control three lights set in the film pressure plate and a fourth cam-microswitch unit starts and stops the camera drive motor at the start and finish of the camera traverse. A manual switch may be used for starting and stopping the camera drive motor.

The power supply consists of two, 6-volt, 100-amp-hr storage batteries, connected in series, which form the 12-volt input to an aircraft-type inverter which generates the 120-volt, 3-phase, 400-cycle alternating current necessary to drive the camera motor. A Frahm frequency meter is installed across one phase in order to give a continual indication of the frequency output, and a voltmeter, placed across the battery terminals, indicates battery voltage level.

The batteries, as well as spare batteries, the voltmeter, inverter, film drums, tools, and so forth are all housed in a weatherproof box and the camera-plate assembly is also covered, when not in use, with a metal weatherproof housing.

The camera normally takes 200-foot reels of film which, for the landing speeds of present-day transport aircraft, makes possible the recording of 20 to 40 landings per roll. Exposures are made through a Wratten K-1 filter on high-speed panchromatic film.

DESIGN CONSIDERATIONS

Because a simple data reduction in obtaining the aircraft vertical velocity at contact was desired and the most direct means appeared to be a measurement of the change of vertical displacement occurring in a given time, a photographic method based on this consideration was sought. With the requirement of an allowable maximum error of ±0.25 fps in vertical velocity and the assumption of a conservative value for vertical acceleration, the height above the runway before touchdown at which measurements would have to be made and the time within which measurements would have to commence in order to determine vertical velocities before touchdown could be determined in the following manner:

From the basic equation

$$\Delta S = V_c t + \frac{1}{2} at^2 \tag{1}$$

it is seen that

$$V_c = \frac{\Delta S}{t} - \frac{1}{2} at \tag{2}$$

where

ΔS vertical displacement during time t, positive downward, ft

V_c contact vertical velocity, positive downward, fps

a vertical acceleration, assumed constant during time t, positive downward, ft/sec^2

t time interval in which ΔS occurs, sec

The vertical acceleration a is not determined, and the data reduction therefore is based on $V_c = \frac{\Delta S}{t}$. But, from equation (2) the error caused by neglecting the acceleration is seen to be $\frac{1}{2}$ at. For an allowable maximum error of ±0.25 fps, an acceleration value of approximately 1/8 g or 4 ft/sec^2 (a conservative value for large airplanes) can be assumed; then for an allowable error of ±0.25 fps

$$t = \frac{0.25}{a/2} = 0.125 \text{ sec}$$

It is then seen that, for an allowable maximum error in vertical velocity within ±0.25 fps, the measurement of displacement must be made within approximately 0.125 second of landing contact if the acceleration is to be neglected. As an example, assume airplane vertical velocities of 2 fps and 10 fps, and consider the time before landing contact as 0.125 second; then S, the maximum displacement above the runway at which measurement may be started, is

$$S = 2 \text{ fps} \times 0.125 \text{ sec} = 0.25 \text{ ft} = 3 \text{ in.}$$

$$S = 10 \text{ fps} \times 0.125 \text{ sec} = 1.25 \text{ ft} = 15 \text{ in.}$$

If all the error in vertical velocity of ±0.25 fps is assumed to be introduced by the measurement of ΔS, then at any vertical velocity, the tolerable error in ΔS would be 0.375 inch, as can be seen by the following illustrations:

At a vertical velocity of 2 fps, the percent error is

$$\frac{0.25 \text{ fps}}{2 \text{ fps}} \times 100 = 12\frac{1}{2} \text{ percent}$$

Since measurement is started at 3 inches above the runway, the error in measurement must be $12\frac{1}{2}$ percent of 3 inches or 0.375 inch.

At a vertical velocity of 10 fps, the percent error is

$$\frac{0.25 \text{ fps}}{10 \text{ fps}} \times 100 = 2.5 \text{ percent}$$

Since measurement is started at 15 inches above the runway, the error in measurement is 2.5 percent of 15 inches or 0.375 inch. The total allowable error of the two position measurements made in determining ΔS must therefore be less than ± 0.375 inch.

In brief, by taking measurements of ΔS within 0.125 second of landing-gear touchdown and to within an accuracy of ± 0.375 inch, vertical velocities, with airplane accelerations neglected, may be calculated to within a probable error of ± 0.25 fps. The error in the time measurement of 0.125 second should be small enough so that its contribution to total-velocity error will be small. From what has already been calculated, it appears that an error of ± 1 percent in the time interval would be satisfactory.

Since ΔS must be measured to within ± 0.375 inch for two position measurements or within approximately ± 0.188 inch for each measurement, a suitable magnification factor (image-object ratio) can be chosen. Since film can be read to ± 0.001 inch or less, a magnification factor of about 1:200 or 1:250 would appear to be reasonable. A choice of lens focal length can now be made. Inasmuch as several good-quality 40-inch telephoto lenses were available, their depths of field were calculated based on a circle of confusion of 0.002 inch. From the calculated depth of field and a range of 800 feet based on the indicated magnification factors, a runway length of about 900 feet could be covered. Larger focal lengths would allow greater operating distances from the runway and smaller focal lengths would mean operating closer to the runway. Inasmuch as use of a 40-inch lens would give operating ranges and runway coverage of the proper order of magnitude and one was readily available, its choice seemed logical. Calculations to determine the film-frame size showed that a 35-millimeter camera would give coverage for all the vertical velocities normally encountered at a 1:200 to 1:250 or greater magnification factor with sufficient leeway for faulty airplane tracking.

Frame and shutter speeds are next considered. Frame speed is partly determined by exposure requirements and partly by the number of frames necessary to be read within approximately 0.125 second - the time requirement necessary to eliminate the acceleration term. At least two frames would have to be read, but a 3- or 4-frame interval would result in increased accuracy. With 0.125 second for four frames (a 3-frame interval), 24 frames per second would result. Because the Mitchell camera, which was available, could be readily adapted to frame speeds of this order and the film footage per landing would not be excessive, this frame speed appeared suitable. Determination can now be made of a proper shutter speed.

In order to realize the desired accuracy in reading the film, the shutter must effectively stop the airplane image motion. At the same time the shutter speed must be limited in order to obtain a satisfactory exposure. Tests showed that a 1/600-second focal-plane shutter would give excellent results with regard to stopping airplane motion and obtaining sufficient exposure. A 1/1200-second shutter, though increasing runway sharpness and accuracy of time determination, offered little advantage over the 1/600-second shutter because it reduced exposure. Shutter speeds under 1/600 second produced blur and decreased the time-factor accuracy.

If the airplane wheel appears at the opposite extreme edges of the film frames, an error of ±1/600 second in time would result with use of the 1/600-second shutter. Since the wheel image must appear inside the frame and not at the extremes in order to be read, the error would only be approximately ±0.001 second. Time-interval measurements will have to be made to within ±1 percent to nullify the effect on probable error in vertical velocity. By use of a synchronous motor and a Frahm frequency meter which is accurate to ±0.5 percent over the temperature ranges normally encountered, the time interval can be determined to within approximately ±0.5 percent.

For tracking the airplane, an optical sight giving a wide field of view with a cross-hair reticle for pinpointing the landing gear appeared to be required. A simple optical gunsight equipped with a cross-hair reticle proved most satisfactory. Also, inasmuch as the camera would track in azimuth only, the camera shaft would have to be accurately righted normal to the earth's horizontal; provision for leveling the camera would be necessary; and the camera shaft would have to rotate in bearings with little or no play.

For the leveling requirements, if an airplane horizontal landing speed of 120 fps and an accuracy of vertical velocity of 1/4 fps or less are assumed, leveling would have to be better than 1/4 part in 120 or 1:480. However, the airplane-wheel image could appear at either side of the film frame so that the airplane would appear to have a vertical velocity merely because the reference line was tilted from the horizontal. Since the film-frame width is approximately 1 inch, a reference line canted as much as 0.001 inch would give an error equal to about 1/4 fps at the most. The film-frame reference line would therefore have to be leveled to at least 1 part in 1,000. The leveling of the film-frame reference line thus determines the leveling requirement of the whole system, and, after allowances have been made for trailer settling, possible shifting due to operator movement, and other causes, leveling to 1 part in 4,000 or better allows a reasonable safety factor with decreased probable error from the leveling source.

At operating ranges of 750 feet to 950 feet, air refraction (atmospheric shimmer) might cause apparent displacement effects which would lead to errors in vertical-velocity calculations.

Since it is necessary to know which wheel touches first, both wheels must be kept in the film frame while tracking. At large camera-axis angles from the normal to the runway, this becomes difficult because of the oblique spread of the wheels. For this reason and in order to keep the depth of field within a circle of confusion of 0.002 inch, angular limits from the normal to the runway were set at $\pm 30^{\circ}$. At a normal distance of 800 feet from the center line of the runway this range gives a coverage of 920 feet of runway length.

Because the camera sweeps a circular arc and the aircraft traverses a path perpendicular to the normal line from the camera to the runway, airplane touchdown will occur at different distances from the camera and different film magnifications will result. This magnification and range can be accounted for to ± 1 percent on a well-defined film image - the magnification factor being obtained by using a known dimension on the airplane, such as the wheel hub, and measuring the hub image on the film. When this procedure is not feasible, the angle between the point of touchdown and the camera normal as measured from the camera and the normal distance to the center of runway would give the range, provided the aircraft landed along the runway center line. The magnification factor would be obtained by the use of the focal length of the lens and the calculated range. Landing deviations from the center line would give errors which would normally not exceed ± 3 percent of the contact vertical velocity.

Because the optical axis is usually above or below the point on the airplane to which measurements are being made, a correction to measured vertical velocity is necessary. The effect of this axis deviation, depending on whether the airplane is approaching the normal or departing from it at time of touchdown and whether the point on the airplane to which measurements are being made is above or below the optical axis, is an apparent error in vertical displacement and thus in vertical velocity.

DATA REDUCTION

Theoretical considerations.- By means of figure 4 and the derivation which follows, the corrections to measured vertical velocity caused by the fact that the optical axis is above or below the point on the airplane to which measurements are being made are shown to be dependent only on the following: airplane horizontal velocity just prior to touchdown, the vertical distance between the optical axis and the point on the airplane to which measurements are being made, and the sine of the angular deviation of touchdown position from the normal to the runway.

From the plan view in figure 4,

$$X = (R + r)\sin\theta \tag{3}$$

and

$$(R + r)^2 = X^2 + R^2$$

Therefore,

$$\frac{dr}{dt}(R + r) = X\frac{dX}{dt} \tag{4}$$

$$\frac{dr}{dt} = \sin\theta\,\frac{dX}{dt} \tag{5}$$

From the side elevation in figure 4,

$$\frac{r}{h} = \frac{R + r}{H}$$

Therefore,

$$(R + r)\frac{dh}{dt} = \frac{dr}{dt}(H - h)$$

$$\frac{dr}{dt} = \frac{(R + r)dh/dt}{H - h} \tag{6}$$

Substituting the value of dr/dt from equation (6) into equation (5) yields

$$\frac{dh}{dt} = \frac{V_H(H - h)\sin\theta}{L} \tag{7}$$

where

R	normal distance to center line of runway, ft
θ	angle of deviation of airplane touchdown position from normal to runway from camera, deg
X	distance of point of touchdown from normal, ft
r	difference in range from normal to actual touchdown, ft
H	height of optical axis above runway, ft
h	apparent altitude of airplane wheel above runway due to range difference from normal, ft
V_H	horizontal velocity of airplane just prior to touchdown, dX/dt, fps
L	range of airplane at touchdown, $R + r$, ft
$\frac{dh}{dt}$	error in vertical velocity, fps
$H - h$	distance between optical axis and point on airplane to which measurements are made, ft
$(H - h)_1$	distance on film between optical axis to point on airplane to which measurements are made, in.

Since the film is used for making measurements, equation (7) in terms of film values becomes

$$\frac{dh}{dt} = \frac{V_H(H - h)_1 \sin \theta}{\text{Focal length}} \tag{8}$$

From equation (8), it is seen that angular deviations from normal position must be known. A binary light-code system employing three lights, placed in the film pressure plate, and three cams operating the light switches were installed to give angular coding for the entire $\pm 30^{\circ}$ with 5° coded range intervals. However, by interpolation, this angle can be determined to within $\pm 2^{\circ}$ or less.

From the geometry shown in figure 4, as the aircraft approaches the normal, if the point to which measurements are made is below the optical axis, the correction in vertical velocity is subtracted; if above, added.

As the aircraft departs from the normal, if the point is below the optical axis, the correction is added; if above, subtracted. Figure 5 is a graph giving the correction values to be applied to the vertical velocity for different angles from the normal at touchdown and for different products of horizontal velocity and the length, measured on the film, from the optical center to the point on the airplane to which measurements are being made.

Procedure.- The data-reduction procedure is as follows:

(1) The film records are examined and the point of touchdown, which is found by locating the frame where tire smoking begins or, if no smoke is visible, where tire flattening is incipient, is marked (see fig. 6); the first and fifth frames previous to touchdown are also marked on the film for each landing. When the film records are being taken, data sheets giving the following information are kept: landing number, time, date, airplane type, airline, first wheel to touch, inverter-frequency reading, wind direction, wind velocity, temperature, and weather condition. It will be noted that a 4-frame interval is read instead of a 3-frame interval. This 4-frame interval occurs in 0.16 second instead of 0.125 second and the longer time is permissible in view of the fact that the aircraft accelerations encountered are actually lower than those assumed in determining the maximum reading time for eliminating the acceleration term.

(2) The angle at which touchdown occurred, before or after the normal position, is obtained from the light-spot code recorded on the film to within $\pm 1^\circ$ or $\pm 2^\circ$ by interpolation.

(3) The magnification factor, necessary for computing vertical velocities, may be obtained from the ratio of the known airplane wheel-rim diameter to that of the wheel-rim diameter measured on the film. This ratio will also give range at touchdown. For decreased data-reduction effort, however, at slight increase in probable error, the magnification factor may be derived by using the distance to the runway center line, as obtained by a transit survey, divided by the cosine of the angular deviation from normal at touchdown.

(4) The height of a fixed point (usually the wheel rim or the tire rim) on the aircraft from the film reference datum is read for the first and fifth film frames before touchdown for each wheel. The difference in height above the reference between frames 1 and 5 multiplied by the magnification factor gives the uncorrected vertical displacement occurring in a 4-frame interval. By dividing the vertical displacement by the time interval for four frames, after correcting the time interval for inverter-frequency variations from 400 cps, the uncorrected vertical velocity is obtained.

(5) The correction due to angular deviation at point of touchdown from normal and the height of the camera axis above or below the point on the airplane to which measurements are being made is made by using figure 5. The airplane horizontal velocities required may be computed from the film, or average values for horizontal velocities of the various aircraft may be used with insignificant error.

(6) The vertical velocity of the center of gravity of the airplane can be approximated by taking the average of the vertical velocities of the right and left wheels immediately before the first wheel makes contact with the runway. This procedure assumes negligible pitching of the airplane.

PRECISION

Errors may result from the following:

(1) Neglecting the acceleration term in the displacement equation. Errors as high as ±0.25 fps may result.

(2) Measurement errors on the film. Distances are measured on the film to within ±0.001 inch. With a magnification factor of 1:250 (equivalent to a range slightly over 800 feet), an error as high as ±0.25 fps may result. Since two position (frame) measurements are made, this error must be accounted for twice.

(3) Determination of range at touchdown. If the range is determined by measurement of the magnification from known airplane dimensions, it can be obtained to within ±1 percent. Based on a vertical velocity of 10 fps, this error in range would mean an error of ±0.1 fps in vertical velocity. If the range is obtained by use of the normal distance to the center line divided by the cosine of the angular deviation from normal at touchdown, errors as high as 5 percent of the vertical velocity may occur for aircraft that may be as much as 40 feet away from the center line of the runway.

(4) Use of a focal-plane shutter. The use of the focal-plane shutter operating at 1/600-second exposure may cause an error of ±0.001 second, as was previously explained. This error is equivalent to ±0.6 percent in a time of 0.16 second and amounts to ±0.06 fps in 10 fps.

(5) Air refraction or shimmer. This factor produced no readable error on the film for the weather conditions which existed at the time the tests were made to evaluate this effect. The tests were made during a time when rather severe turbulent effects were apparent.

(6) Biaxial leveling of the camera and righting of the shaft axis. The high quality of leveling precision and the ability of the unit to maintain a level condition under field use makes this source of error insignificant. For righting the shaft axis a level indicating 1 part in 28,000 per division is used. The camera cross level is accurate to close to 1 part in 2,000 per division.

(7) Film shrinkage and expansion. These effects are caused by temperature, humidity, and processing changes and the errors are of the order of $\pm 1/2$ percent. Based on a vertical velocity of 10 fps, this error would amount to ± 0.05 fps, which is negligible.

(8) Shutter timing. A period of at least five film frames (0.2 second) elapses before the camera drive is up to uniform speed from the time the camera begins to operate. This source of error is eliminated by commencing camera operation and tracking sufficiently early so that the camera is up to uniform speed before touchdown occurs. If touchdown should occur before the camera is up to uniform speed, the record obtained should be discarded. The frequency meter used for determining true frame speed is accurate to ± 0.5 percent over normal operating temperatures. The time interval of 0.160 second may therefore be in error by ± 0.5 percent which amounts to ± 0.05 fps in 10 fps.

By considering the maximum errors which may occur due to the above sources, the probable maximum error, if measured magnifications are used, is

$$0.675\left(0.25^2 + 0.25^2 + 0.25^2 + 0.1^2 + 0.06^2 + 0.05^2 + 0.05^2\right)^{1/2} = 0.31 \text{ fps}$$

If the range in item (3) is determined by using the normal distance and the deviation angle, the probable error should be determined by substituting this error for the value previously used in the equation.

DISCUSSION

The instrument can be set up and made ready for operation within 1 hour. If the trailer remains in position, the instrument can be made ready for subsequent operations within 10 minutes. This time includes that necessary to make leveling checks and minor leveling adjustments. The instrument operation does not interfere with aircraft or airport operation and requires no installation of equipment on the aircraft. The pilot is also unaware that pictures are being taken because of the large operating distance from the runway. Where airport conditions offer very restricted instrument locations and trailer movement is discouraged, smaller fixed units may be installed with less objection.

Although very good film records have been taken on dull cloudy days and although records of nonvisual approach landings may be obtained when low vertical ceilings exist, this method is essentially useful for obtaining visual-approach landing data. Occasionally landings may occur outside of the camera-runway coverage (short or long landings). Photographic limitations, however, cause the loss of these landings. In practice, these losses were found to amount to approximately 5 percent.

A typical landing record (fig. 7) shows that the acceleration values are small. Also, from the same figure, it can be seen that little error would be made in vertical-velocity determination if touchdown was determined incorrectly by one or two film frames. Figure 8, which is the vertical-velocity curve obtained by differentiating the vertical-displacement curve of figure 7, shows that a 1- or 2-frame error in determining touchdown would affect the vertical velocity negligibly. From 0.16 second to 0 second before touchdown, the acceleration equals 0.1g or less; whereas, at 0.25 second or more before touchdown, the acceleration equals roughly 1/6g. Since this landing is a typical one, the assumed values chosen for the evaluation of acceleration errors appear to be of the proper order of magnitude.

The data reduction was found to be uncomplicated and relatively fast. The film reading time per landing for obtaining vertical velocity was 5 minutes or less.

Vertical-velocity measurements can be made within a probable error of ±0.31 fps, and it was found that a large number of landings could be recorded quickly and economically.

Since vertical velocities are measured from a horizontal datum, landing-gear loads due to possible runway inclinations are not evaluated. Additional information such as roll attitude angle, rolling velocity, and horizontal velocities immediately prior to touchdown can be readily obtained from the film records.

CONCLUDING REMARKS

A photographic method employing a long-focal-length (40-inch) lens for obtaining statistical data on vertical velocities of aircraft immediately prior to landing contact was developed for use with land-based airplanes. The use of the method and equipment seems feasible and practical. Large numbers of landings can be recorded in relatively short periods and data can be obtained easily and economically. The accuracy of the vertical-velocity measurement is within ±0.31 fps.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 4, 1953.

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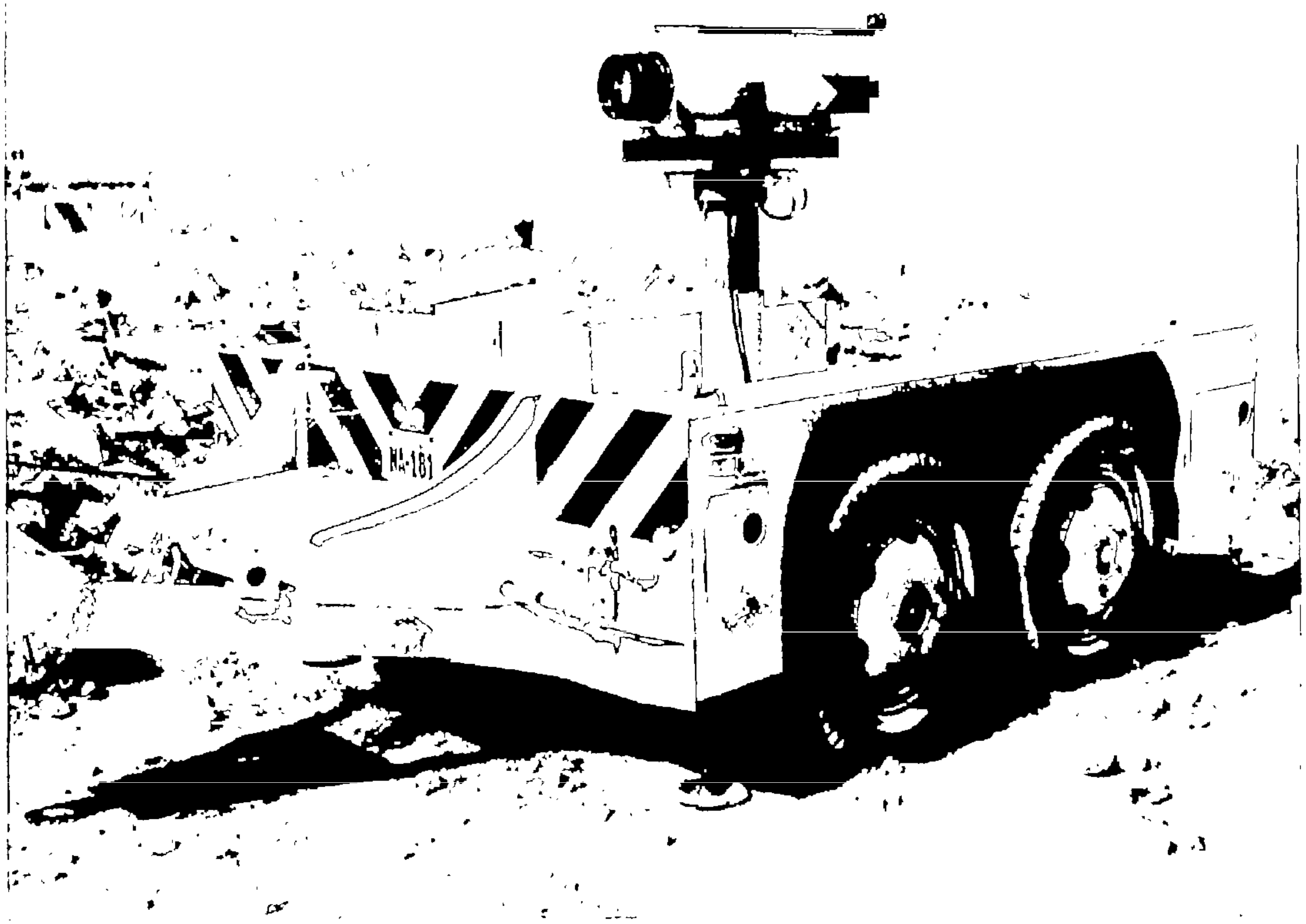

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Figure 1.- The complete instrument unit as installed at Washington National Airport.

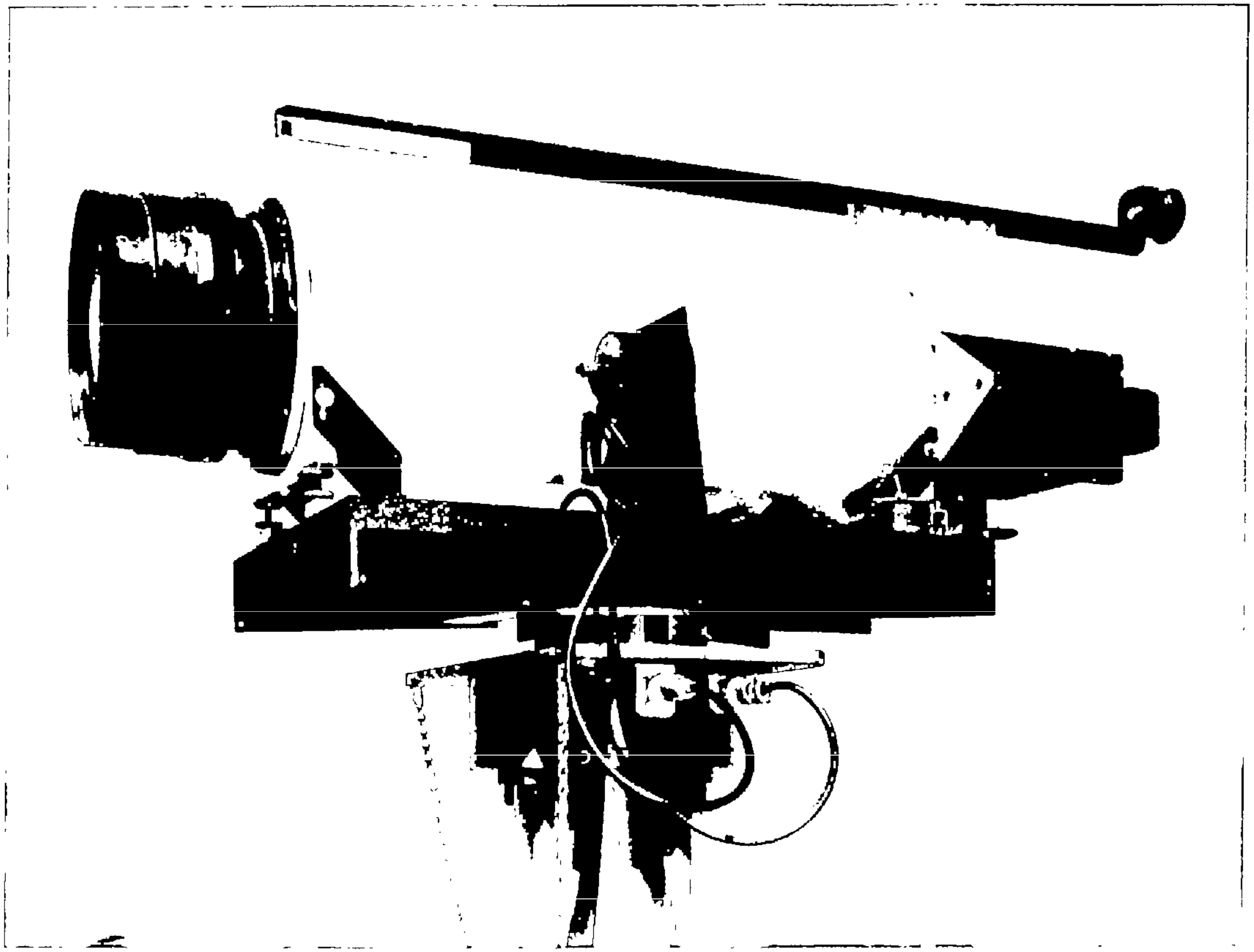

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Figure 2.- A closeup of the components that are mounted on the shaft and shaft housing.

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Figure 3.- Operator position at the commencement of a landing approach.

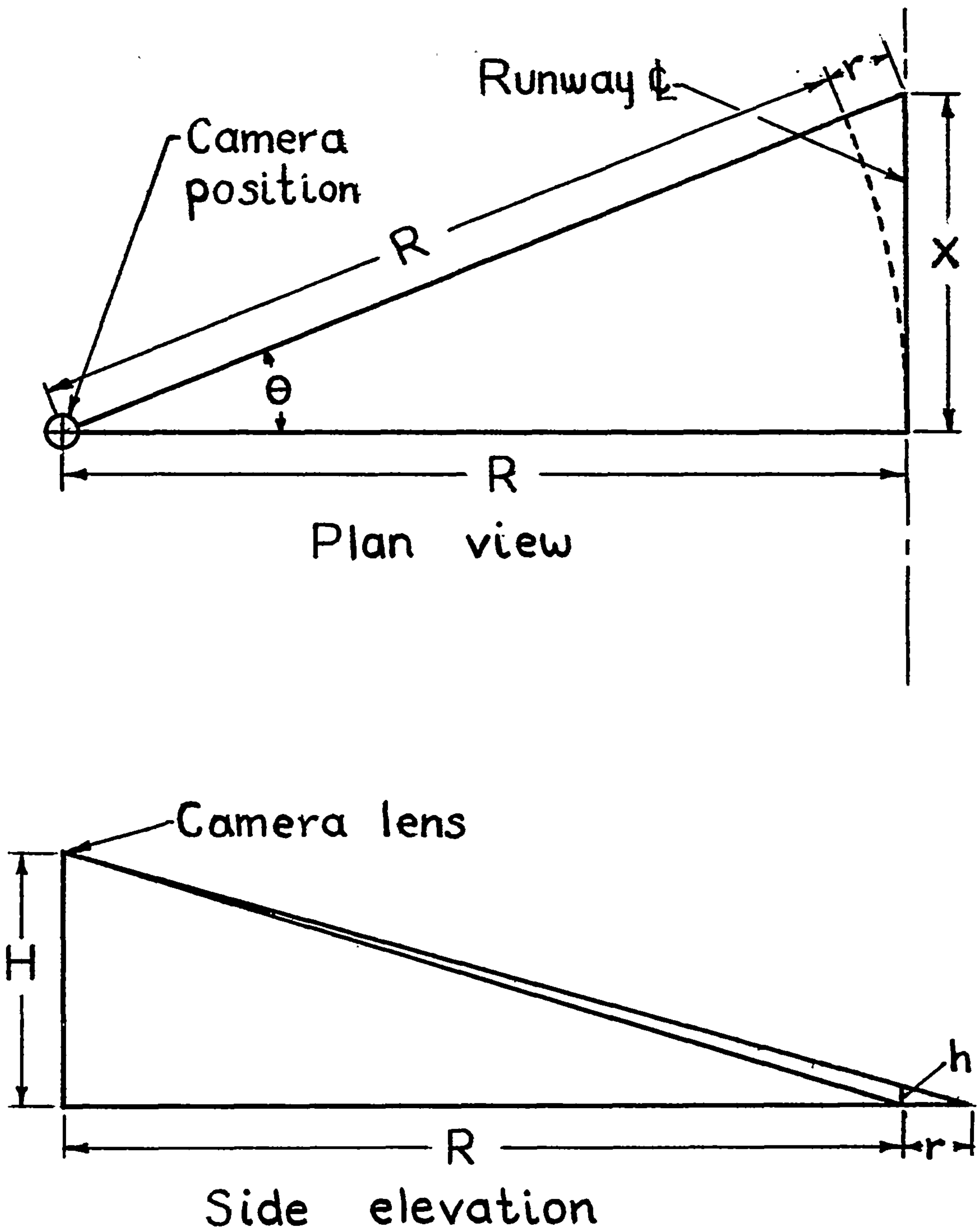

Figure 4.- Apparent vertical displacement of airplane due to angular deviation of touchdown position from the normal and due to the fact that camera axis is above point on airplane to which measurements are made.

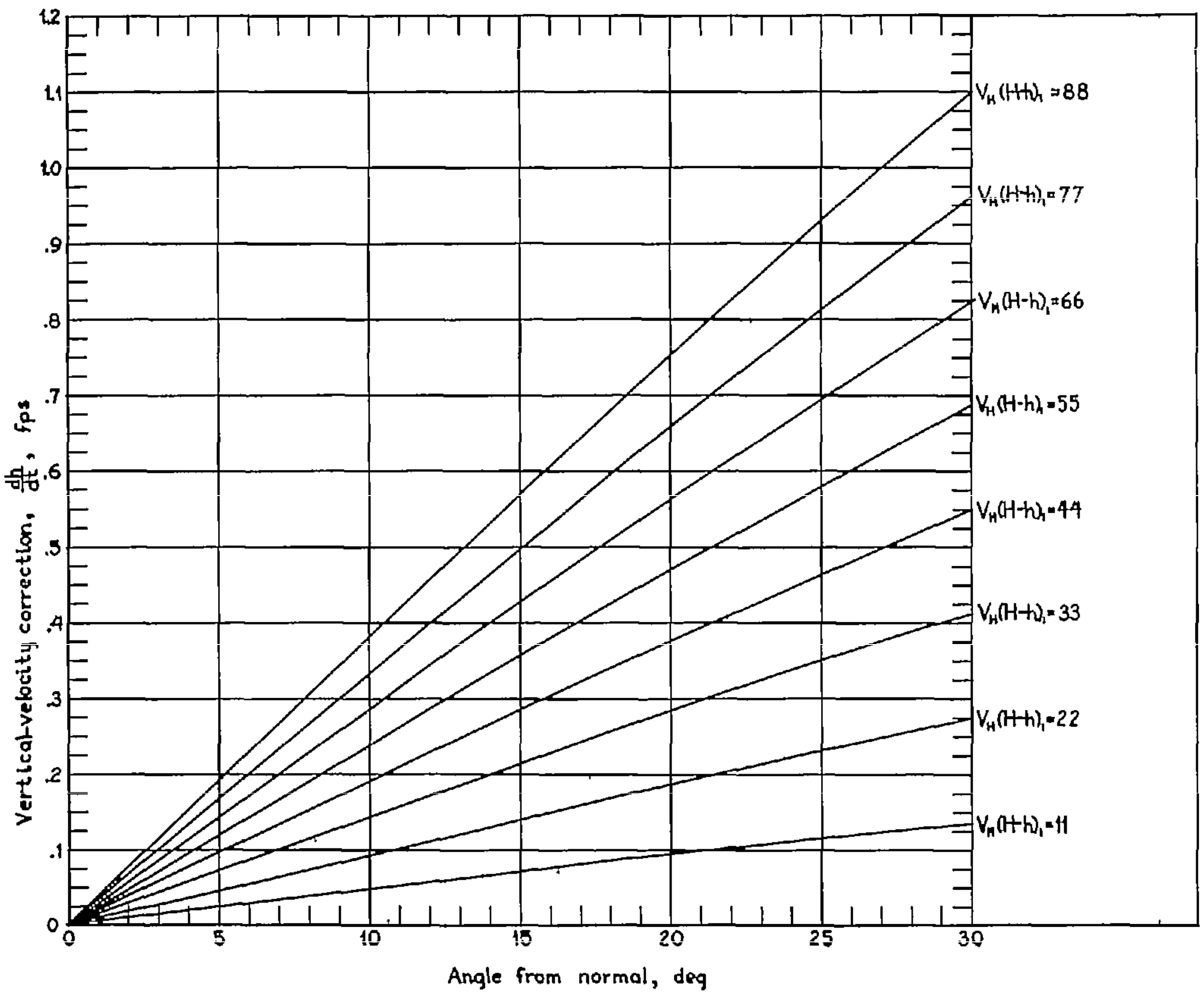

Figure 5.- The corrections to vertical velocity required because of camera height and angular deviation from normal at touchdown.

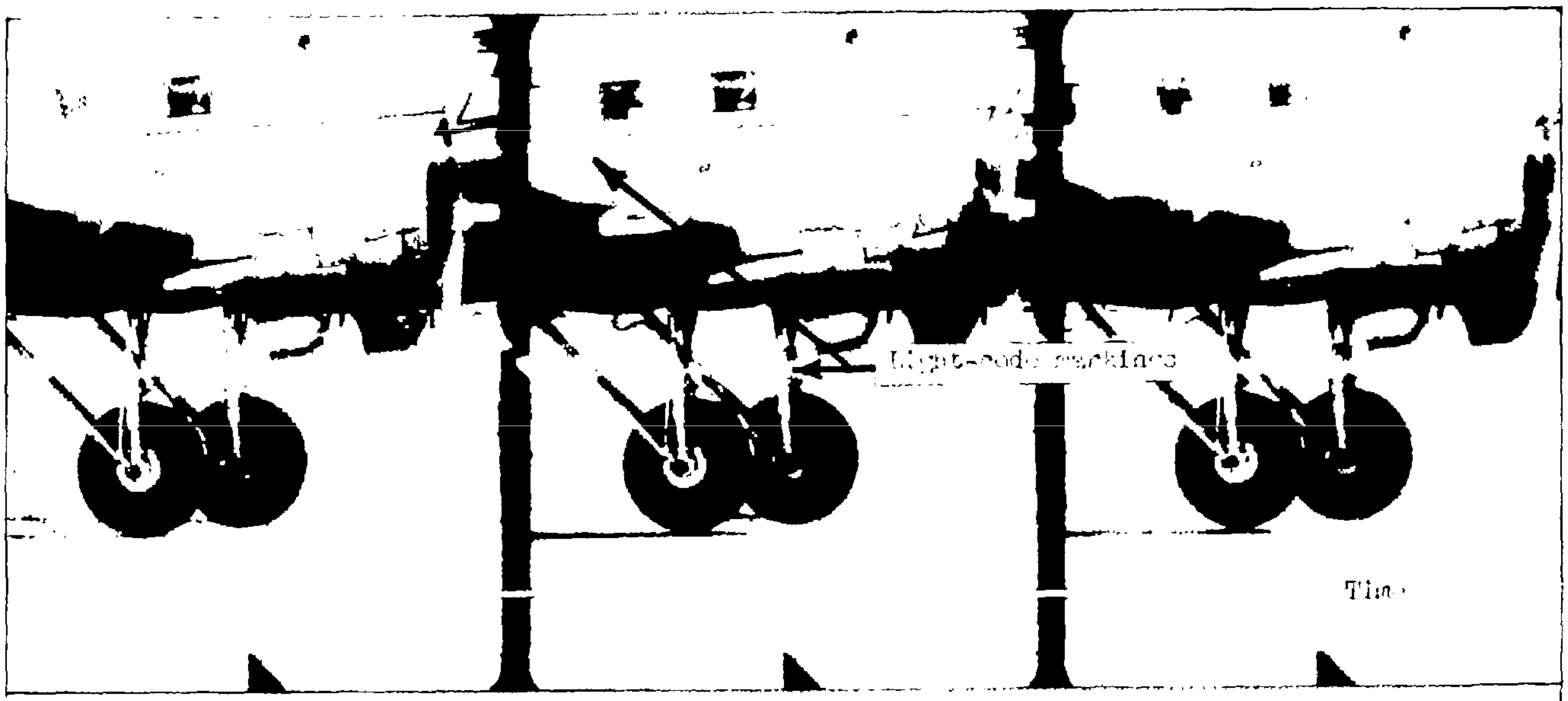

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Figure 6.- Actual film-frame sequence showing the point of touchdown, light coding, and film markings.

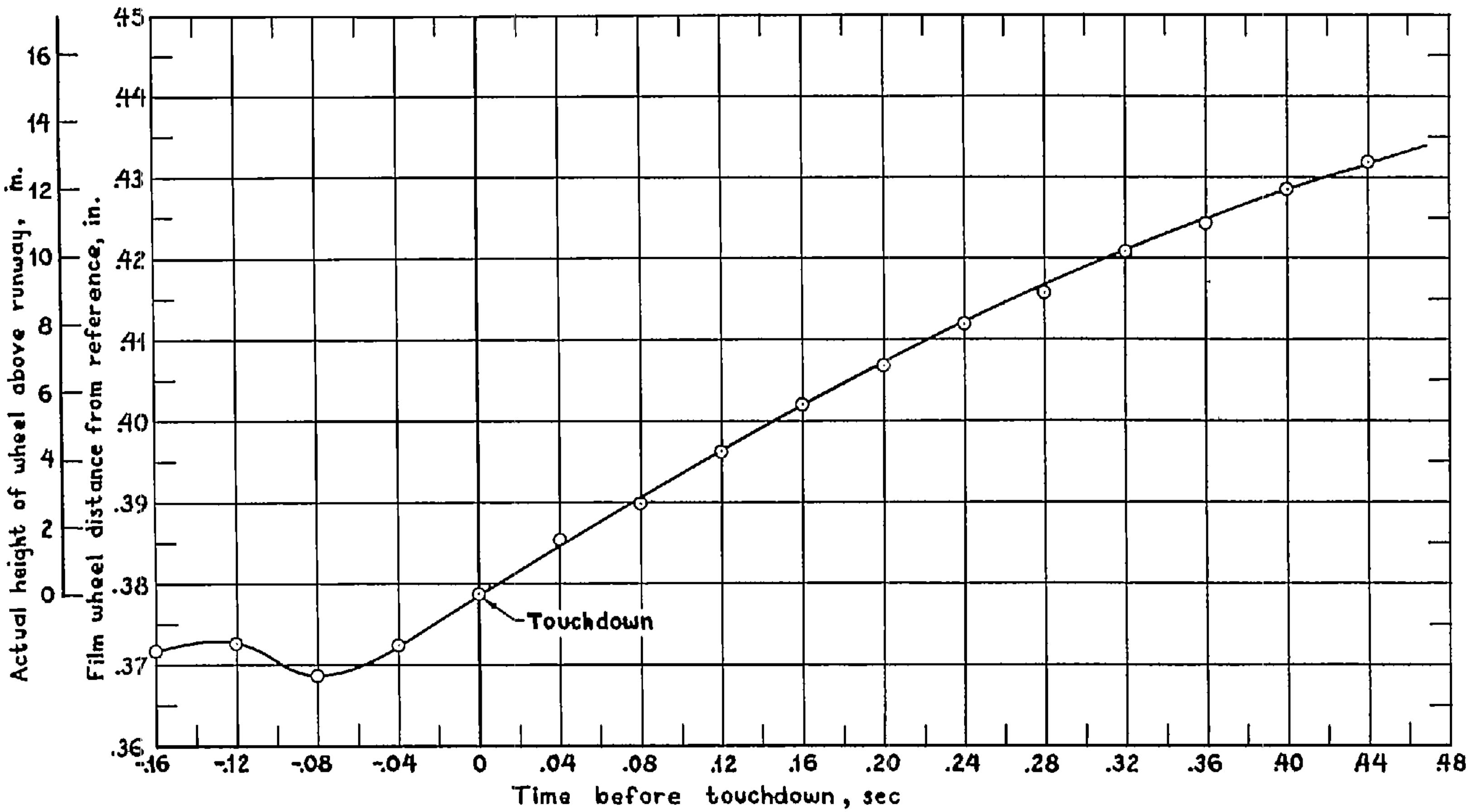

Figure 7.- Plot of film distances from the film reference to the top of the left wheel before and after touchdown and the same quantities expressed as actual wheel height above the runway before touchdown.

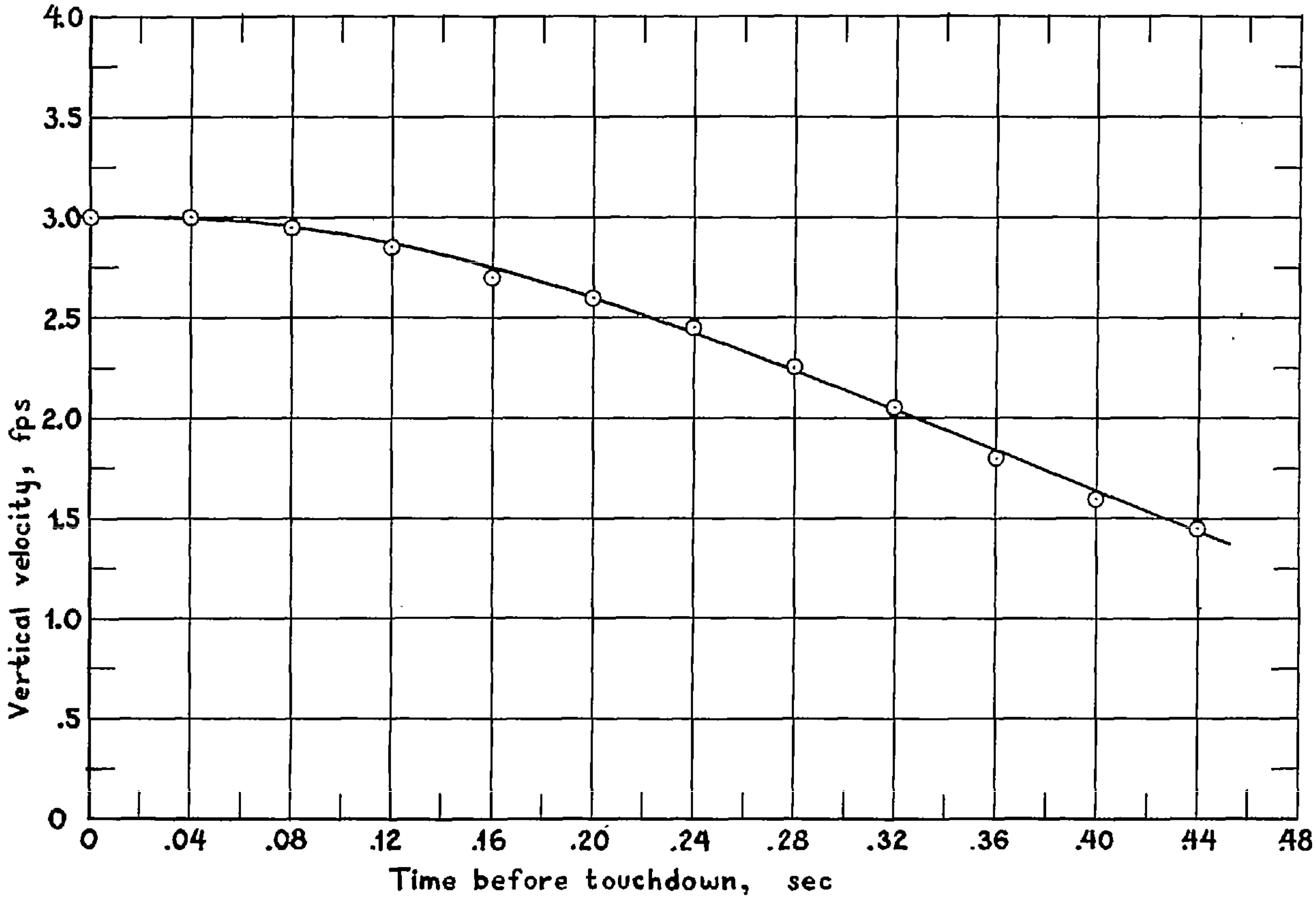

Figure 8.- Vertical velocity of the left wheel immediately prior to touchdown as differentiated from the displacement curve in figure 7.

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